FINAL REPORT

ONR GRANT NUMBER N00014-91-J-1557

NUMERICAL SIMULATION OF CROSS-SHELF EXCHANGE AND MIXING IN THE COASTAL TRANSITION ZONE

Dr. Dale Haidvogel
Institute of Marine and Coastal Sciences
Rutgers University
P.O. Box 231
New Brunswick, NJ 08903-0231
dale@ahab.rutgers.edu

February 3, 1995

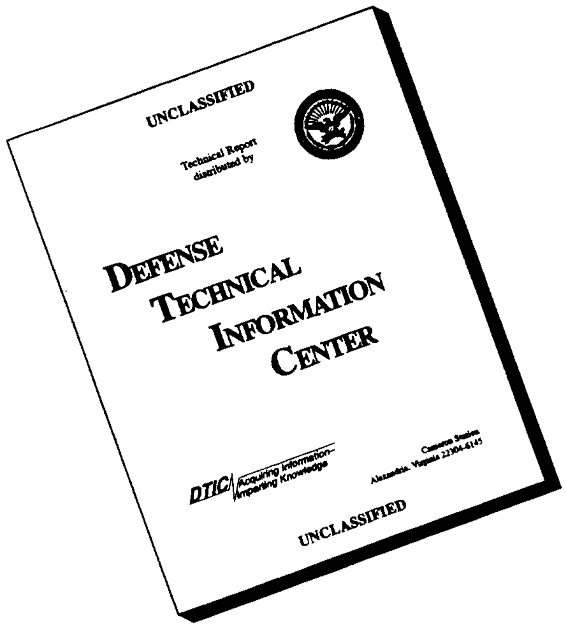
Goals

The long-term goals of our coastal research at Rutgers include: (1) the implementation and testing of numerical models suitable for regional problems featuring irregular coastlines, steep topography, and strong coastal/deep ocean interaction; (2) the use of these models to simulate the regional response of coastal currents, fronts, and eddies in the California Current System; (3) the simulation of storm-driven sediment transport and wind-driven upwelling in the Middle Atlantic Bight; (4) the determination of the local balances of heat, mass and energy in these regions, including the patterns and methods of their exchange across the shelf/deep ocean boundary; and (5) the application of these regional models to the study of coupled physical/biogeochemical processes. ONR N00014-91-J-1557 produced results pertinent to issues (1), (2), (4) and (5).

Results Under ONR N00014-91-J-1557

Using the semi-spectral primitive equation model of Haidvogel et al. (1991b; development supported by N00014-86-K-0751), the evolution of a forced, surface-intensified eastern boundary current has been studied in the presence of both finite-amplitude topography and irregular coastal geometry (Haidvogel et al., 1991a).

DISCLAIMER NOTICE



THIS DOCUMENT IS BEST QUALITY AVAILABLE. THE COPY FURNISHED TO DTIC CONTAINED A SIGNIFICANT NUMBER OF PAGES WHICH DO NOT REPRODUCE LEGIBLY.

The laminar surface current quickly evolves away from its smooth intial conditions and approaches a turbulent, time-dependent equilibrium featuring an intense, meandering along-shore jet with local velocities of 80-100 cm/sec. A deep, poleward undercurrent also forms. Subsequent interaction with the protruding cape geometry causes an offshore deflection in the steepening frontal meanders, some of which produce elongated filaments which penetrate significant distances (400-500 km) offshore. The emerging filaments are characterized by a strong downwelling signal (maximum vertical velocities of 30-40 meters per day). The simulated filaments ultimately pinch off, typically within 40-50 days, to form a co-rotating pair of detached eddies. The existence of the cape geometry, as well as the southward surface flow, are necessary for filament generation: removal of the irregular coastline or reversal of the sense of the surface circulation inhibit filament formation. Detailed analysis of the instantaneous and time-mean momentum balances shows strong dynamical similarity to observations taken during the Coastal Transition Zone experiment, and confirms that eddy transport mechanisms are responsible for the maintenance of the poleward undercurrent. Offshore transport of heat by the filaments, found to be O(0.02) petawatts, is substantial.

General transport patterns and residence times in the upper 100 meters of the Coastal Transition Zone (CTZ) were studied using simulated Lagrangian drifter experiments (Hofmann et al., 1991). The circulation fields used for the experiments were obtained from numerical simulation described above. The composite drifter trajectories show that transport patterns and residence times in the upper 100 meters are determined by the proximity of the drifter release point to the offshore-flowing filament. The magnitude of the offshore displacement of the simulated drifters implies substantial cross-jet exchange. In particular, comparison of the simulated drifter trajectories with the trajectory followed by a drifter released during the 1988 CTZ field experiment supports the hypothesis that the deepening of the abundance maxima observed in certain zooplankton distributions resulted from these populations being downwelled as they were transported offshore by the flow associated with the filament observed in 1988.

The three-dimensional CTZ model has been coupled to a nine-component food web model and a bio-optical model (Moisan et al., 1995). The resulting simulated three-dimensional nutrient, plankton and submarine light fields agree well with those observed within the CTZ. Specifically, high nutrient and plankton biomass occur onshore and within the core of the simulated filament. The depth of the 1 percent light level shallows to less than 30 meters in regions of high phytoplankton biomass and deepens to greater than 75 meters in regions of low phytoplankton biomass. The integrated carbon transport for the model varied with distance from shore and is highest in the region where the filament circulation pattern develops a counter-rotating pair of offshore eddies. The annual integrated carbon transport is estimated to be 1.89×10^{12} grams C.

The model used by Haidvogel et al (1991a) to simulate filament evolution in the Coastal Transition Zone has been redesigned to permit accurate simulation of coupled coastal/deep ocean interaction on both regional and basin scales. A semi-implicit coastal ocean circulation model using a generalized topography-following coordinate system has been implemented, shown to perform well on representative test problems, including the evolution of the diurnal mixed layer. These tests, conducted in both one and two dimensions, show that the model handles mixed layer cycling quite well even in the presence of strong variations in topography (maximum to minimum depth ratios of order 100; Song and Haidvogel, 1994a). A successive set of simulations of the California Current System featuring alongshore variations in wind stress and coastline geometry have also been conducted (Song and Haidvogel, 1994b).

Publications

Haidvogel, D.B., A. Beckmann and K.S. Hedstrom, 1991a: Dynamical simulations of filament formation and evolution in the Coastal Transition Zone. J. Geophys. Res., 96, 15,017-15,040.

Haidvogel, D.B., J. Wilkin and R. Young, 1991b: A semi-spectral ocean circulation model using vertical sigma and orthogonal curvilinear horizontal coordinates. J. Comp. Phys., 94, 151-185.

Hofmann, E.E., K.S. Hedstrom, J.R. Moisan, D.B. Haidvogel and D.L. Mackas, 1991: Use of simulated drifter tracks to investigate general transport patterns and residence times in the Coastal Transition Zone. J. Geophys. Res., 96, 15,041-15,052.

Moisan, J.R., E.E. Hofmann and D.B. Haidvogel, 1995: Modeling nutrient and plankton processes in the California Coastal Transition Zone. 2. A three-diemnsional physical-biological model. J. Geophys. Res., submitted.

Song, Y. and D.B. Haidvogel, 1994a: A semi-implicit ocean circulation model using a generalized topography-following coordinate system. J. Comp. Phys., 115, 228-244.

Song, Y. and D.B. Haidvogel, 1994b: Numerical simulations of the CCS under the joint effects of coastal geometry and surface forcing. In: Estuarine and Costal Modeling III, Malcolm Spaulding et al., eds.; ASCE, New York; 682 pp.

Reprinted from Estuarine and Coastal Modeling III
Proceedings of the 3rd International Conference
Sponsored by the Waterway, Port, Coastal and Ocean Div./ASCE
September 8-10, 1993, Oak Brook, Illinois

Numerical Simulations of the CCS under the Joint Effects of Coastal Geometry and Surface Forcing

Yuhe Song* and Dale Haidvogel†

Abstract

Using the S–Coordinate Rutgers University Model (SCRUM) of Song and Haidvogel(1993), a coupled coastal (86 m depth) and deep ocean (4600 m depth) California Coastal region has been investigated for the dynamics of the California Current System (CCS) under the joint effects of realistic coastline geometry, bottom topography, wind forcing, and surface heat flux. The model equations are the three–dimensional, free surface, primitive equations with orthogonal curvilinear coordinates in the horizontal and the s–coordinate in the vertical. Three kinds of surface forces—steady wind field with positive curl, long-term oscillatory wind, and diurnal cycling wind and thermal forcing—are used to simulate the variations of the CCS. Two alternate parameterizations, dynamic instability mixing and turbulence closure mixing, are used in the diurnal cycling problem. The model is shown to be stable and capable of handling the joint effects of geometry and surface forcing. Our simulations show that: (1) upwelling and a depressed surface height are always found at the coast for equatorward wind stress; (2) the equatorward surface jet and the poleward undercurrent persist for all upwelling-favorable winds; (3) a meandering jet and eddies can be caused by the coastline geometry and wind curl in combination; (4) surface and bottom layers mixing increases the variations of the CCS.

Introduction

There is a great challenge in modeling the coastal oceans due to irregular coastline geometry and severe bottom topography, the latter featuring both shallow coastal water and deep ocean. In part due to this geometric complexity, the coastal oceans are the sites of a variety of physical and coupled physical/biological phenomena. For example, eastern boundary regions are often sites of wind-driven coastal upwelling and surface height slopes downward toward the coast, and strong vertical advection and turbulent mixing due to sur-

*Asst. Res. Prof., Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, NJ 08903

†Prof. II, Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, NJ 08903

A Semi-spectral Primitive Equation Ocean Circulation Model Using Vertical Sigma and Orthogonal Curvilinear Horizontal Coordinates

DALE B. HAIDVOGEL

Chesapeake Bay Institute, The Johns Hopkins University, Baltimore, Maryland 21218

JOHN L. WILKIN

Department of Ocean Engineering, Woods Hole Oceanographic Institution, 98 Water Street, Falmouth, Massachusetts 02543

AND

ROBERTA YOUNG

Department of Earth, Atmospheric and Planetary Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Reprinted from JOURNAL OF COMPUTATIONAL PHYSICS

Vol 94, No 1, May 1991
Printed in Belgium

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 96, NO. C8, PAGES 15,041–15,052, AUGUST 15, 1991

Use of Simulated Drifter Tracks to Investigate General Transport Patterns and Residence Times in the Coastal Transition Zone

EILEEN E. HOFMANN,[1] KATHERINE S. HEDSTRÖM,[2,3] JOHN R. MOISAN,[1]
DALE B. HAIDVOGEL,[3,4] AND DAVID L. MACKAS[5]

General transport patterns and residence times in the upper 100 m of the coastal transition zone (CTZ) were studied using simulated Lagrangian drifter experiments. The circulation fields used for the drifter experiments were obtained from a regional primitive equation model that incorporates coastal geometry and bottom topography that is representative of the CTZ region. The simulated circulation fields show velocity patterns that are consistent with those associated with the filaments and jets observed in the CTZ region. Drifters were released at 880 points in the model domain in a pattern that bracketed, both horizontally and vertically, the region in which offshore-flowing filaments were observed to form. At each location, drifters were released at depths of 30, 60, 90 m and tracked for 30 days. The depth of these drifters varied along their trajectories in response to the vertical velocities experienced by the drifters. An additional set of drifters was released at 30 m and was constrained to remain at this depth. The composite drifter trajectories show that transport patterns and residence times in the upper 100 m are determined by the proximity of the drifter release point to the offshore-flowing filament. Drifters released inshore of the filament are transported southward with the mean flow of the model California Current. Drifters released near the region in which the filament originates are transported rapidly offshore. The point at which this difference in drifter fate occurs is approximately 100 km offshore. The time required for a drifter to be transported from the nearshore region to the outer boundary of the area covered in the CTZ model domain is approximately 20 days. Comparison of the free-floating drifters with the 30-m fixed-depth drifters shows that the deeper drifters are displaced southward as they are transported offshore in the jet. The magnitude of the southward displacement for the 90-m drifters is about 15 km, implying substantial cross-jet exchange. Comparison of the simulated drifter trajectories with the trajectory followed by a drifter released during the 1988 CTZ field sampling program support the hypothesis that the deepening of the abundance maxima observed in the distributions of *Dolioletta gegenbauri*, juvenile forms of *Euphausia pacifica* and *Eucalanus californicus* resulted from these populations being downwelled as they were transported offshore by the flow associated with the filament observed in 1988.

1. INTRODUCTION

The coastal transition zone (CTZ) off the coast of California (Figure 1) is characterized by meanders of the California Current and by prominent, cross-shelf jets and filaments. The cold filaments can be identified in Advanced Very High Resolution Radiometry [*Breaker and Gilliland*, 1981; *Ikeda and Emery*, 1984] and Coastal Zone Color Scanner imagery [*Abbott and Zion*, 1985, 1987] and are observed to extend several hundred kilometers offshore. Typically, the cold filaments are associated with offshore-flowing jets that have maximum speeds of approximately 50 cm s^{-1}. Several hydrographic surveys [*Rienecker et al.*, 1985; *Flament et al.*, 1985; *Kosro and Huyer*, 1986; *Rienecker and Mooers*, 1989] have been conducted to describe the structure of the cold filaments and jets observed off Point Arena. These studies show that the vertical extent of the offshore jet reaches to approximately 200 m, the offshore jet is about 50 km wide, and often onshore flow is found to the south of the jet. A similar structure was described for a cold filament off Cape Blanco, Oregon [*Moum et al.*, 1988]. The various conceptual models that have been proposed for the formation and maintenance of the cross-shelf jets and filaments are summarized by *Strub et al.* [this issue]. The offshore-flowing jets represent a potentially important mechanism for transporting properties such as nutrients and organic carbon from nearshore to offshore regions. Recently, *Bucklin et al.* [1989] and *Mackas et al.* [this issue] have suggested that the filaments are important in determining the transport and structure of zooplankton populations off northern California.

In 1987 and 1988, a multidisciplinary study of the cold filaments and jets in the CTZ was undertaken [*Coastal Transition Zone Group*, 1988]. These studies have provided hydrographic and velocity measurements, as well as observations of the distribution of nutrients, phytoplankton, and zooplankton in the CTZ study region. Many of the results of the 1987 and 1988 CTZ program are summarized by *Strub et al.* [this issue]. As part of the 1988 CTZ field observations (June–July 1988), a series of drifters were released from late June to early July in a cross-shelf jet [cf. *Strub et al.*, this issue]. The drifter study was similar to that done in the CTZ region in 1987 which is described by *Paduan and Niiler* [1990]. As in 1987 [*Abbott et al.*, 1990], biological and hydrographic observations were made at frequent intervals (i.e., 1–2 days) at the drifter location (Figure 2). The assumption underlying these observations was that the drifter tracked the same water mass during the period encompassed by the sampling.

In addition to the CTZ observational program, there has been a complementary modeling component. As part of the

[1]Department of Oceanography, Old Dominion University, Norfolk, Virginia.
[2]Institute for Naval Oceanography, Stennis Space Center, Mississippi.
[3]Now at Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, New Jersey.
[4]Chesapeake Bay Institute, The Johns Hopkins University, Baltimore, Maryland.
[5]Institute of Ocean Sciences, Sidney, British Columbia, Canada.

Paper number 91JC00832.
0148-0227/91/91JC-00832$05.00

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 96, NO. C8, PAGES 15,017–15,040, AUGUST 15, 1991

Dynamical Simulations of Filament Formation and Evolution in the Coastal Transition Zone

DALE B. HAIDVOGEL,[1] AIKE BECKMANN,[2] AND KATHERINE S. HEDSTRÖM[1]

Chesapeake Bay Institute, Johns Hopkins University, Baltimore, Maryland

Using the semispectral primitive equation model of Haidvogel et al. (1991), the evolution of a forced, surface-intensified, eastern boundary current is studied in the presence of both finite-amplitude topography and irregular coastline geometry. The model domain is 1000 km in alongshore length, and extends on average 700 km in the cross-shelf direction. A representative cape, as well as smoothed continental shelf-slope topography, are included. The model is forced by inclusion of nudging terms in the equations of motion which relax the fluid system back to a prescribed reference state on a time scale of 45 days. The reference state chosen is a broad, geostrophically balanced, equatorward flow having a maximum current at the surface of 0.45 m s^{-1} and a transport of approximately 10 Sv. No explicit wind forcing is included. Initialized with the smooth surface current, the model quickly approaches a turbulent, time-dependent equilibrium featuring an intense, meandering alongshore jet with local velocities of 0.8–1.0 m s^{-1}. A deep, poleward undercurrent also forms. Subsequent interaction with the protruding cape geometry causes an offshore deflection in the steepening frontal meanders, some of which produce elongated filaments which penetrate significant distances (400–500 km) offshore. The emerging filaments are characterized by a strong downwelling signal (maximum vertical velocities of 30–40 m d^{-1}). The simulated filaments ultimately pinch off, typically within 40–50 days, to form a corotating pair of detached eddies. The existence of the cape geometry, as well as the southward surface flow, appears to be necessary in this model to produce filament generation; removal of the irregular coastal geometry or reversal of the sense of the surface circulation is shown to inhibit filament formation. Detailed analysis of both instantaneous and time-mean momentum balances show dynamical similarity to observations taken during the Coastal Transition Zone experiment and elucidate the eddy transport mechanisms responsible for the formation of the poleward undercurrent in these experiments. Offshore transport of heat by the filaments, found to be $O(0.06)$ PW, is substantial.

1. INTRODUCTION

Observational evidence from the Coastal Transition Zone (CTZ) experiment, together with that from prior in situ and remotely sensed measurements collected during the Coastal Ocean Dynamics Experiment (CODE), Ocean Prediction Through Observations Modeling and Analysis (OPTOMA) program, and other programs, provide for the first time a detailed description of the cold, nutrient-rich, offshore-flowing filaments which form during the spring and summer in the California Current system (CCS). Most vividly seen in high-resolution satellite images of sea surface temperature (e.g., Figure 1), the filaments form near the coast, often in proximity to regions of strong coastline curvature, and penetrate hundreds of kilometers across the shelf-slope boundary into the deep ocean. The filaments, although narrow (O(50–75 km) in width) and trapped within a few hundred meters of the surface, are nonetheless associated with intense offshore currents which may approach a meter per second. Strong evidence for systematic downwelling of water parcels by the filaments also exists. The offshore and vertical fluxes of mass, heat, and biological materials associated with these filaments can therefore be substantial and are of likely importance to regional, and perhaps global, physical and biological balances.

The CTZ program was carried out in 1987 and 1988 to further refine our understanding of the dynamical character, temporal variability, and physical-biological implications of the filaments [*Strub et al.*, this issue]. In addition to satellite imagery, extensive hydrographic, biological, microstructure, and moored current meter measurements were collected. (See, for example, *Kosro et al.* [this issue] for a description of the large-scale survey cruises in 1987.) The Lagrangian structure of the filaments was also investigated using surface drifter observations [*Brink et al.*, this issue]. Two examples of the types of data thus sampled are summarized in Figures 2 and 3, which show inferred along-shore, geostrophic currents from the 1988 survey and observed Lagrangian flow structure during July 1988, respectively. Further reference to the observed structure, and dynamical character, of the filaments is also made below in section 6.

Despite the intensive observational effort represented by the CTZ program, the essential nature of the filaments is still open to interpretation. For example, Strub et al. identify three conceptual models which might account for aspects of the observed filament behavior. These are the squirt model (a one-way jet, transporting water of coastal origin to the deep ocean), the eddy model (in which a slowly evolving set of mesoscale eddies extracts fluid from the coastal region), and the meandering jet model (in which steepening meanders on a strong southward jet extend offshore and pinch off, thereby transporting coastal fluid to the deep ocean). None of these conceptual scenarios is ruled out by the present observational data base; however, both the 1987 and 1988 observational surveys are in principle consistent with the

[1]Now at Institute of Marine and Coastal Sciences, Rutgers University, New Brunswick, New Jersey.

[2]Now at Institut für Meereskunde, Universität Kiel, Kiel, Germany.

Paper number 91JC00943.
0148-0227/91/91JC-00943$05.00

A Semi-implicit Ocean Circulation Model Using a Generalized Topography-Following Coordinate System

YUHE SONG AND DALE HAIDVOGEL

Rutgers University, Institute of Marine and Coastal Sciences, P.O. Box 231, New Brunswick, New Jersey 08903

Reprinted from JOURNAL OF COMPUTATIONAL PHYSICS

Vol. 115, No. 1, November 1994
Printed in Belgium

OFFICE OF THE UNDER SECRETARY OF DEFENSE (ACQUISITION)
DEFENSE TECHNICAL INFORMATION CENTER
CAMERON STATION
ALEXANDRIA, VIRGINIA 22304-6145

IN REPLY REFER TO DTIC-OCC

SUBJECT: Distribution Statements on Technical Documents

TO: OFFICE OF NAVAL RESEARCH
CORPORATE PROGRAMS DIVISION
ONR 353
800 NORTH QUINCY STREET
ARLINGTON, VA 22217-5660

1995 1027 030

1. Reference: DoD Directive 5230.24, Distribution Statements on Technical Documents, 18 Mar 87.

2. The Defense Technical Information Center received the enclosed report (referenced below) which is not marked in accordance with the above reference.

FINAL REPORT
N00014-91-J-1557
TITLE: NUMERICAL SIMULATION OF CROSS-SHELF EXCHANGE AND MIXING IN THE COASTAL TRANSITION ZONE

3. We request the appropriate distribution statement be assigned and the report returned to DTIC within 5 working days.

4. Approved distribution statements are listed on the reverse of this letter. If you have any questions regarding these statements, call DTIC's Cataloging Branch, (703) 274-6837.

FOR THE ADMINISTRATOR:

1 Encl

GOPALAKRISHNAN NAIR
Chief, Cataloging Branch

FL-171
Jul 93

DISTRIBUTION STATEMENT A:

APPROVED FOR PUBLIC RELEASE: DISTRIBUTION IS UNLIMITED

DISTRIBUTION STATEMENT B:

DISTRIBUTION AUTHORIZED TO U.S. GOVERNMENT AGENCIES ONLY; (Indicate Reason and Date Below). OTHER REQUESTS FOR THIS DOCUMENT SHALL BE REFERRED TO (Indicate Controlling DoD Office Below).

DISTRIBUTION STATEMENT C:

DISTRIBUTION AUTHORIZED TO U.S. GOVERNMENT AGENCIES AND THEIR CONTRACTORS; (Indicate Reason and Date Below). OTHER REQUESTS FOR THIS DOCUMENT SHALL BE REFERRED TO (Indicate Controlling DoD Office Below).

DISTRIBUTION STATEMENT D:

DISTRIBUTION AUTHORIZED TO DOD AND U.S. DOD CONTRACTORS ONLY; (Indicate Reason and Date Below). OTHER REQUESTS SHALL BE REFERRED TO (Indicate Controlling DoD Office Below).

DISTRIBUTION STATEMENT E:

DISTRIBUTION AUTHORIZED TO DOD COMPONENTS ONLY; (Indicate Reason and Date Below). OTHER REQUESTS SHALL BE REFERRED TO (Indicate Controlling DoD Office Below).

DISTRIBUTION STATEMENT F:

FURTHER DISSEMINATION ONLY AS DIRECTED BY (Indicate Controlling DoD Office and Date Below) or HIGHER DOD AUTHORITY.

DISTRIBUTION STATEMENT X:

DISTRIBUTION AUTHORIZED TO U.S. GOVERNMENT AGENCIES AND PRIVATE INDIVIDUALS OR ENTERPRISES ELIGIBLE TO OBTAIN EXPORT-CONTROLLED TECHNICAL DATA IN ACCORDANCE WITH DOD DIRECTIVE 5230.25, WITHHOLDING OF UNCLASSIFIED TECHNICAL DATA FROM PUBLIC DISCLOSURE, 6 Nov 1984 (Indicate date of determination). CONTROLLING DOD OFFICE IS (Indicate Controlling DoD Office).

The cited documents has been reviewed by competent authority and the following distribution statement is hereby authorized.

A

(Statement)

OFFICE OF NAVAL RESEARCH
CORPORATE PROGRAMS DIVISION
ONR 353
800 NORTH QUINCY STREET
ARLINGTON, VA 22217-5660

(Controlling DoD Office Name)

(Reason)

(Controlling DoD Office Address, City, State, Zip)

Debra T. Hughes

DEBRA T. HUGHES
DEPUTY DIRECTOR
CORPORATE PROGRAMS OFFICE

(Signature & Typed Name)

(Assigning Office)

19 SEP 1995

(Date Statement Assigned)